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Low-carbon economic development in Central Asia based on LMDI decomposition and comparative decoupling analyses

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Abstract: Low-carbon economic development is a strategy that is emerging in response to global climate change. Being the third-largest energy base in the world, Central Asia should adopt rational and efficient energy utilization to achieve the sustainable economic development. In this study, the logarithmic mean Divisia index (LMDI) decomposition method was used to explore the influence factors of CO_2 emissions in Central Asia (including Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan and Turkmenistan) during the period 1992–2014. Moreover, decoupling elasticity and decoupling index based on the LMDI decomposition results were employed to explore the relationship between economic growth and CO_2 emissions during the study period. Our results show that the total CO_2 emissions decreased during the period 1992–1998, influenced by the collapse of the Soviet Union in 1991 and the subsequent financial crisis. After 1998, the total CO_2 emissions started to increase slowly along with the economic growth after the market economic reform. Energy-related CO_2 emissions increased in Central Asia, mainly driven by economic activity effect and population effect, while energy intensity effect and energy carbon structure effect were the primary factors inhibiting CO_2 emissions. The contribution percentages of these four factors (economic activity effect, population effect, energy intensity effect and energy carbon structure effect) to the total CO_2 emissions were 11.80%, 39.08%, –44.82% and –4.32%, respectively, during the study period. Kazakhstan, Uzbekistan and Turkmenistan released great quantities of CO_2 with the annual average emissions of 189.69×10^6, 45.55×10^6 and 115.38×10^6 t, respectively. In fact, their economic developments depended on high-carbon energies. The decoupling indices clarified the relationship between CO_2 emissions and economic growth, highlighting the occurrence of a "weak decoupling" between these two variables in Central Asia. In conclusion, our results indicate that CO_2 emissions are still not completely decoupled from economic growth in Central Asia. Based on these results, we suggest four key policy suggestions in this paper to help Central Asia to reduce CO_2 emissions and build a resource-conserving and environment-friendly society.

Keywords: energy-related CO_2 emissions; low-carbon economy; LMDI decomposition; decoupling elasticity; decoupling index; Central Asia

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1 Introduction

Given the significant influence of climate warming on social and economic development, the interest in low-carbon economy has grown globally (Olcott, 2006; Pablo-Romero et al., 2017). The essence of low-carbon economy is to cut the link between economic growth and greenhouse gas emissions, for example through energy technology and policy innovations (Mohsen et al., 2016; Nepal et al., 2017; Wang et al., 2017). A correct understanding of the changing relationship between economic growth and greenhouse gas emissions is hence needed to evaluate the realization of a regional low-carbon economy and formulate a dedicated development strategy.

Earlier studies on the relationship between energy consumption and economic development have been based on the environmental Kuznets hypothesis, the gray relational degree method, the co-integration relationship, and the coordination degree model (Organization for Economic Co-operation and Development, 2005; Feng et al., 2011; Zhang et al., 2011; Wang et al., 2012). Since the 21st century, however, researches in this field have been mainly based on the environmental Kuznets curve (EKC) and decoupling theories.

In the EKC theory, the curve describing the relationship between carbon emissions and environmental growth is simulated using historical experience data (Oh and Yun, 2014; Asane-Otoo, 2016). This technique is highly sensitive to sample selection, data selection and measurement methods; hence, there is no consensus on the carbon emissions calculated based on this theory. The decoupling theory can be used to calculate the synchronicity between economic growth and resource consumption rates.

An early decoupling index was defined as the ratio between the ending and the initial values of the ratio between environmental pressure and gross domestic product (GDP). This decoupling index could effectively identify the occurrence of decoupling, but it could not distinguish different decoupling states (Hunt, 1994; Organization for Economic Co-operation and Development, 2005). Later, the Tapio decoupling index was proposed to study the relationship between carbon emissions and economic growth in Europe during the period 1970–2001 (Tapio, 2005). This index overcomes the sensitivity of the early decoupling model to the base period and presents a notable decoupling state recognition ability; hence, it is widely used in empirical research (Gao et al., 2012; Liu et al., 2014).

The decomposition of the driving factors of carbon emissions (i.e., Kaya identity) was proposed by Kaya (1983) and it includes the Divisia and the Laspeyres indices as factor decomposition methods. Sun (1998) improved the residual problems of the Laspeyres index; additionally, Ang and Zhang (2000) proposed the logarithmic-mean Divisia index (LMDI), which can decompose multiple factors of carbon emissions and reduce the residual error to 0. Therefore, the LMDI is widely applied to the factor decomposition of energy-related carbon emissions (Wang et al., 2011; Hu et al., 2014). For example, Lai and Zheng (2017) analyzed the carbon emissions from industrial energy consumption in Dalian City of China using the LMDI model. This work took into account energy structure, energy intensity, industrial structure and output scale. Yao et al. (2018) used the LMDI model to study the driving effect of spatial differences in provincial water consumption, decomposing the driving effect into intensity, structure, income and population effects.

Central Asia is one of the most environmentally vulnerable regions in the world. It has abundant energy resources, perhaps exceeding those in Kuwait, the Gulf of Mexico and the North Sea (Dorian et al., 2006; Mercure and Salas, 2012). Since the beginning of the 21st century, increasing energy consumption in Central Asia resulted in higher CO_2 emissions, further increasing the temperature in Central Asian arid region by approximately 1°C–2°C (Lioubimtseva and Henebry, 2009). In order to reduce such high CO_2 emissions, it is essential to develop a low-carbon economy in this area.

In this study, we examined the influence factors of energy-related CO_2 emissions in Central Asia by applying the LMDI model. Moreover, we explored the relationship between CO_2 emissions and economic growth according to the Tapio decoupling model and a decoupling index. The overall aim of this study was to provide a scientific reference for the development of a low-carbon economy, to reduce CO_2 emissions and ultimately to alleviate climate change in Central Asia.

2 Materials and methods

2.1 Study area

In its narrow sense, Central Asia includes five countries (i.e., Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan and Turkmenistan) located between 46°28′–87°29′E and 35°08′–55°25′N. This is at the same time one of the most sparsely populated areas in the world, with a total area of about 4.00×10^6 km^2 (Siegfried et al., 2012; Mannig et al., 2013). It is also a geopolitical center, connecting many regions of the Northern Hemisphere.

Landforms in Central Asia are higher in the southeast than in the northwest. The mountains located in the southeastern area (Eurasian hinterland) block the warm-humid airflow from the Indian and Pacific oceans, maintaining a temperate continental climate in this region. The most prominent climate feature is the rare occurrence of precipitation (average annual precipitation <300 mm; Mannig et al., 2013), combined with strong solar radiation and high evaporation. The total population in Central Asia amounts to 67.70×10^6, while cultivated lands occupy an area of 32.30×10^6 hm^2 and water resources amount to 25.00×10^{10} m^3 (Yao et al., 2013).

Additionally, Central Asia has abundant energy resources. Specifically, its energy reserves are the third in the world, surpassed only by those in the Middle East and Siberia (Dorian, 2006). Kazakhstan, Turkmenistan, Uzbekistan, Kyrgyzstan and Tajikistan possess energy reserves of 26.90×10^9, 3.30×10^9, 4.41×10^9, 0.59×10^9 and 0.51×10^9 t, respectively (Cobanli, 2014). As a matter of fact, such energy resources have been at the core of the industrial development of Kazakhstan, Turkmenistan and Uzbekistan, favoring their rapid economic growth. However, agriculture still remains the main industry in Tajikistan and Kyrgyzstan.

2.2 Data sources

The data of CO_2 emissions, human population, GDP and energy use for each Central Asian country during the period 1992–2014 were obtained from the World Bank (http://data.worldbank.org.cn). We converted the GDP data to constant 2010 USD in order to eliminate the inflation effect, and also transformed all the energy use data into their oil-equivalent. Finally, we obtained all energy consumption data from the Carbon Dioxide Information Analysis Center (CDIAC; http://cdiac.ess-dive.lbl.gov).

2.3 Methods

2.3.1 Decoupling elasticity

The decoupling elasticity theory was first proposed by Tapio (2005) for the processing of causal relationships among variables. The results of this method can be divided into three statuses (i.e., connection, decoupling and negative decoupling) corresponding to three threshold values (0.0, 0.8 and 1.2, respectively). These statuses can be further subdivided into eight categories (i.e., strong decoupling, weak decoupling, strong negative decoupling, weak negative decoupling, expansive negative decoupling, expansive connection, recessive decoupling and recessive connection; Fig. 1) by the following equation:

$$\beta=\left(\frac{\Delta C}{C^0}\right)\Big/\left(\frac{\Delta G}{G^0}\right), \tag{1}$$

where β is the decoupling elasticity indicator of CO_2 emissions and economic growth; ΔC and ΔG refer to the changes in CO_2 emissions (t) and GDP growth (USD), respectively; and C^0 and G^0 are the CO_2 emissions (t) and the GDP (USD) in the baseline year (1992).

2.3.2 Kaya identity

The Kaya identity was proposed by Kaya (1990) during the first IPCC seminar as a mean of decomposing carbon emissions. It can be expressed as follows:

$$C=\sum_j C_j=\sum_j P\times\frac{G}{P}\times\frac{E}{G}\times\frac{C}{E}=\sum_j P\times A\times I\times S, \tag{2}$$

where C, P, G and E refer to the total energy-related CO_2 emissions (t), regional population, gross

domestic product at constant 2010 prices (USD) and total end-use energy consumption (t), respectively; and j represents the year. The Kaya identity reveals the impact factors of CO_2 emissions: P expresses the population growth as a determinant of energy demand (i.e., the population effect; unit: people), A refers to the increase in CO_2 emissions caused by per capita GDP growth (i.e., the economic active effect; unit: USD/people), I corresponds to the energy consumption per unit of GDP (i.e., the energy intensity effect; unit: t/USD), and S describes the CO_2 emissions per unit of energy consumption (i.e., the energy carbon structure effect).

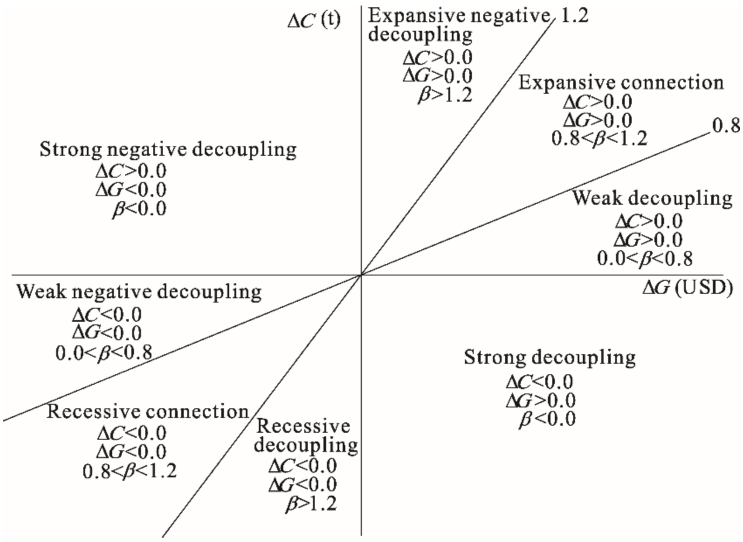

Fig. 1 Classification of decoupling elasticity between CO_2 emissions and economic growth. ΔC, changes in CO_2 emissions (t); ΔG, changes in GDP growth (USD); β, the decoupling elasticity indicator of CO_2 emissions and economic growth.

2.3.3 LMDI decomposition method

The LMDI decomposition method includes an additive version and a multiplicative version, whose results are similar. In this paper, we applied the additive decomposition method, which can be expressed by the following equations:

$$\Delta C_{\text{tot}} = C^t - C^0 = \Delta C_{\text{pop}}^t + \Delta C_{\text{act}}^t + \Delta C_{\text{int}}^t + \Delta C_{\text{str}}^t, \tag{3}$$

$$\Delta C_{\text{pop}}^t = \sum_i w \ln \frac{P^t}{P^0}, \tag{4}$$

$$\Delta C_{\text{act}}^t = \sum_i w \ln \frac{A^t}{A^0}, \tag{5}$$

$$\Delta C_{\text{int}}^t = \sum_i w \ln \frac{I^t}{I^0}, \tag{6}$$

$$\Delta C_{\text{str}}^t = \sum_i w \ln \frac{S^t}{S^0}, \tag{7}$$

$$w = \frac{C_i^t - C_i^0}{\ln C^t - \ln C^0}, \tag{8}$$

where ΔC_{tot} indicates the increment in the total CO_2 emissions (t) from year t to year 0; C^t and C^0 represent CO_2 emissions (t) in year t and in the baseline year (1992); ΔC_{pop}^t, ΔC_{act}^t, ΔC_{int}^t and ΔC_{str}^t indicate the changes in CO_2 emissions (t) linked to population, economic activity, energy intensity and energy carbon structure effects, respectively; w indicates the estimated weight; i represents the

year; P^0, A^0, I^0 and S^0 are the population effect, economic activity effect, energy intensity effect and energy carbon structure effect in the baseline year (1992), respectively; and P^t, A^t, I^t and S^t are the population effect, economic activity effect, energy intensity effect and energy carbon structure effect in the i^{th} year, respectively.

2.3.4 Decoupling index

We applied a novel decoupling method to verify the relationship between economic growth and CO_2 emissions in Central Asia, based on the results of the additive LMDI method (Diakoulaki and Mandaraka, 2007; Vehmas et al., 2007). The advantage of this approach is that it can achieve the decoupling target for each factor, rather than providing a rough and superficial relationship between economic growth and CO_2 emissions (Wang et al., 2016). Here, we could identify which factor(s) enhanced or curtailed CO_2 emissions to what extent. The method can be expressed by the following equations:

$$\Delta E_t = \Delta C_{\text{tot}} - \Delta C_{\text{act}}^t = \Delta C_{\text{pop}}^t + \Delta C_{\text{int}}^t + \Delta C_{\text{str}}^t , \tag{9}$$

$$\delta = -\frac{\Delta E_t}{\Delta C_{\text{act}}^t} = -\frac{\Delta C_{\text{pop}}^t}{\Delta C_{\text{act}}^t} - \frac{\Delta C_{\text{int}}^t}{\Delta C_{\text{act}}^t} - \frac{\Delta C_{\text{str}}^t}{\Delta C_{\text{act}}^t} = \delta_{\text{pop}}^t + \delta_{\text{int}}^t + \delta_{\text{str}}^t , \tag{10}$$

where, ΔE_t represents the total inhibiting effect on CO_2 emissions (t); δ is the total decoupling index; and δ_{pop}^t, δ_{int}^t and δ_{str}^t represent the decoupling in population, energy intensity and energy carbon structure in the i^{th} year, respectively. δ values can be ≥ 1, between 0 and 1, or ≤ 1, indicating strong, weak, or null decoupling, respectively.

3 Results and discussion

3.1 CO_2 emission trajectories

3.1.1 CO_2 emissions across Central Asia

We calculated the change rates of the total CO_2 emissions and per capita CO_2 emissions in Central Asia during the period 1992–2014 (Fig. 2). In accordance with the change trends, we subdivided the study period into two stages: 1992–1998 and 1999–2014.

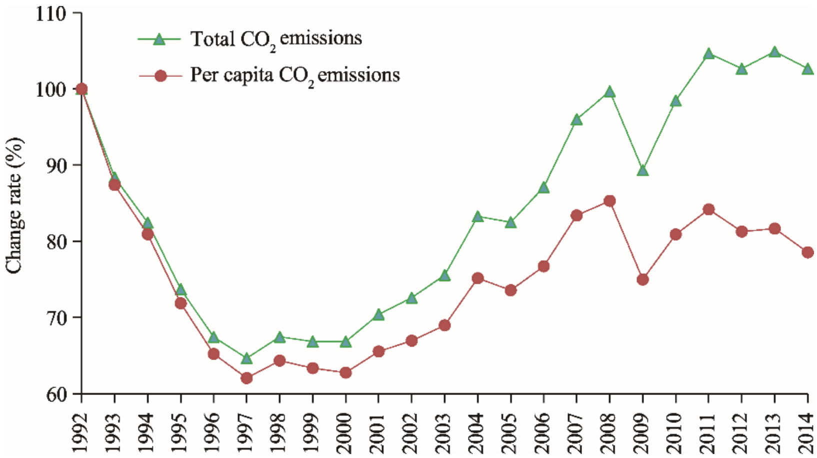

Fig. 2 Change rates of the total CO_2 emissions and per capita CO_2 emissions in Central Asia from 1992 to 2014 (using 1992 as the baseline year)

During the first stage (1992–1998), the total CO_2 emissions and per capita CO_2 emissions decreased (average annual growth rates of –6.35% and –7.09%, respectively). The growth decrease can be attributed to the collapse of the Soviet Union in 1991 and to the Asian financial crisis in 1998 (Rowland, 2001; Mao, 2014). Following independence, the industrial sector of each Central Asian country lacked equipment and production capacity. Hence, the five analyzed countries endured

considerable economic recession and population emigration, resulting in low energy consumption and CO_2 emissions.

During the second stage (1999–2014), the total CO_2 emissions and per capita CO_2 emissions increased (average annual growth rates of 2.90% and 1.44%, respectively). It should be noted that a great increase occurred during 1999–2008, after the successful implementation of the market economic reform (Plyshevskii, 2014). However, this was followed by a sharp reduction during 2008–2009, related to the global financial crisis of September 2008 (Ruziev and Majidov, 2013). After this short phase, Central Asian countries benefited from the improvements of the international macro-economy and financial environment, reflected by an increase in the total CO_2 emissions and per capita CO_2 emissions from 2009 to 2011. Finally, during 2012–2014, carbon emissions were put under control and even slightly decreased due to the implementation of environmental protection laws and regulations (Nepal et al., 2017).

Overall, the total CO_2 emissions and per capita CO_2 emissions in Central Asia reflected the economic development of this region. However, the population growth after year 1998 maintained the per capita CO_2 emissions at a relatively low level.

3.1.2 CO_2 emissions in each of the five Central Asian countries

Kazakhstan, Uzbekistan and Turkmenistan are listed among the top 100 countries in the world for heavy CO_2 emissions (Dorian, 2006; González, 2015). CO_2 emissions in these three countries during the study period 1992–2014 are shown in Figure 3. In fact, Kazakhstan, Uzbekistan and Turkmenistan are rich in energy resources and are rapidly developing their industries by using high-carbon energies (e.g., coal, oil and natural gas; Dorian, 2006). However, in Kyrgyzstan and Tajikistan, CO_2 emissions changed only slightly during the study period, since the two countries have relatively weak industrial bases and their economic developments depend mainly on agricultural production (Tang and Chen, 2015).

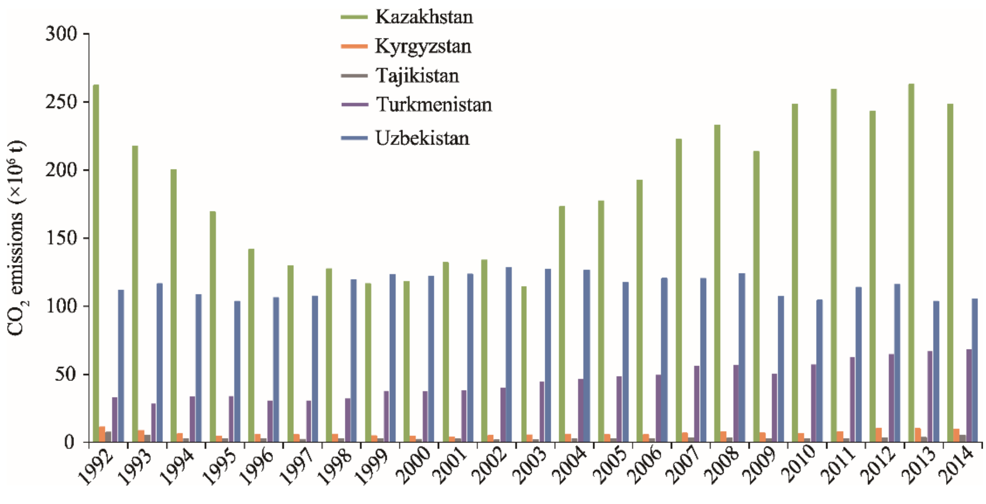

Fig. 3 CO_2 emissions in Central Asian countries during 1992–2014

3.2 Decoupling elasticity between CO_2 emissions and economic growth

The relationship between economic growth and CO_2 emissions was investigated by considering yearly decoupling elasticity data in the framework of the Tapio decoupling model (Table 1). We identified five different decoupling statuses in Central Asia: strong decoupling, weak decoupling, recessive decoupling, expansive negative decoupling and weak negative decoupling. Specifically, strong decoupling occurred mainly during the periods of 1996–1997 and 1999–2000, and in the years 2005, 2009, 2012 and 2014. During these periods or in these years, CO_2 emissions changed heavily, while economic growth did not. Weak decoupling occurred during the periods of 2001–2004, 2006–2008 and 2010–2011, and in the year of 2013. During these periods or in this year, economic growth prompted an increase in CO_2 emissions; moreover, economic growth rates were

higher than CO_2 emission rates. Recessionary decoupling occurred in 1993 and 1995, due to the collapse of the Soviet Union. All Central Asian countries experienced unstable political and economic environments during the early years of independence, leading to a decrease in industrial output and CO_2 emissions.

Table 1 Results of decoupling elasticity in Central Asia during 1992–2014

Time period	ΔC (t)	ΔG (USD)	β	Status
1992–1993	–0.1162	–0.0762	1.5254	RD
1993–1994	–0.0592	–0.1146	0.5169	WND
1994–1995	–0.0874	–0.0557	1.5695	RD
1995–1996	–0.0627	0.0076	–8.2545	SD
1996–1997	–0.0278	0.0095	–2.9118	SD
1997–1998	0.0280	0.0031	8.9549	END
1998–1999	–0.0061	0.0340	–0.1808	SD
1999–2000	–0.0001	0.0642	–0.0021	SD
2000–2001	0.0358	0.0908	0.3943	WD
2001–2002	0.0219	0.0726	0.3021	WD
2002–2003	0.0296	0.0810	0.3649	WD
2003–2004	0.0771	0.0985	0.7826	WD
2004–2005	–0.0077	0.1115	–0.0695	SD
2005–2006	0.0462	0.1310	0.3525	WD
2006–2007	0.0890	0.1344	0.6623	WD
2007–2008	0.0368	0.0873	0.4211	WD
2008–2009	–0.1035	0.0495	–2.0919	SD
2009–2010	0.0914	0.1297	0.7049	WD
2010–2011	0.0618	0.1538	0.4017	WD
2011–2012	–0.0200	0.1218	–0.1639	SD
2012–2013	0.0224	0.1489	0.1505	WD
2013–2014	–0.0224	0.1287	–0.1738	SD

Note: ΔC, the changes in CO_2 emissions (t); ΔG, the changes in GDP growth (USD); β, the decoupling elasticity indicator of CO_2 emissions and economic growth; RD, recessive decoupling; WND, weak negative decoupling; WD, weak decoupling; SD, strong decoupling; END, expensive negative decoupling.

3.3 Decomposition of CO_2 emissions

3.3.1 LMDI decomposition of CO_2 emissions in Central Asia

The results of decoupling elasticity (Table 1) indicated that there was a significant environmental pressure on economic growth and CO_2 emissions in Central Asia. Therefore, it is necessary to analyze the factors influencing CO_2 emissions in order to achieve the emission reduction target.

The additive LMDI method was applied to decompose the total CO_2 emissions in Central Asia into four influence factors (population effect, economic activity effect, energy intensity effect and energy carbon structure effect). The annual contribution percentage of each factor to the total CO_2 emissions is shown in Figure 4. Among these four factors, the economic active effect and population effect were generally responsible for the observed increases in CO_2 emissions. The economic active effect contributed the most to CO_2 emissions (approximately 25.44×10^7 t; contribution percentage of 39.08%) during 1992–2014. Meanwhile, the population effect contributed with about 76.80×10^6 t CO_2 emissions (contribution percentage of 11.80%). The energy intensity effect and energy carbon structure effect mainly played inhibiting roles, decreasing CO_2 emissions. Specifically, the energy intensity effect was more significant in reducing CO_2 emissions during 1992–2014, with a reduction of approximately -291.78×10^6 t (contribution percentage of –44.82%). The energy carbon structure effect showed an inconsistent pattern, lowering CO_2 emissions by about -28.09×10^6 t (contribution percentage of –4.32%).

Overall, the cumulative change in the total CO_2 emissions increased in time during the study

period 1992–2014, except the periods of 1992–1998 (i.e., the transition stage from planned economy to market economy) and 2008–2009 (i.e., the start of the global financial crisis). The total CO_2 emissions increased just by 11.33×10^6 t by the year 2014, compared to the baseline year 1992, due to the impacts of social-economic developments and the energy use structure in Central Asia during the study period.

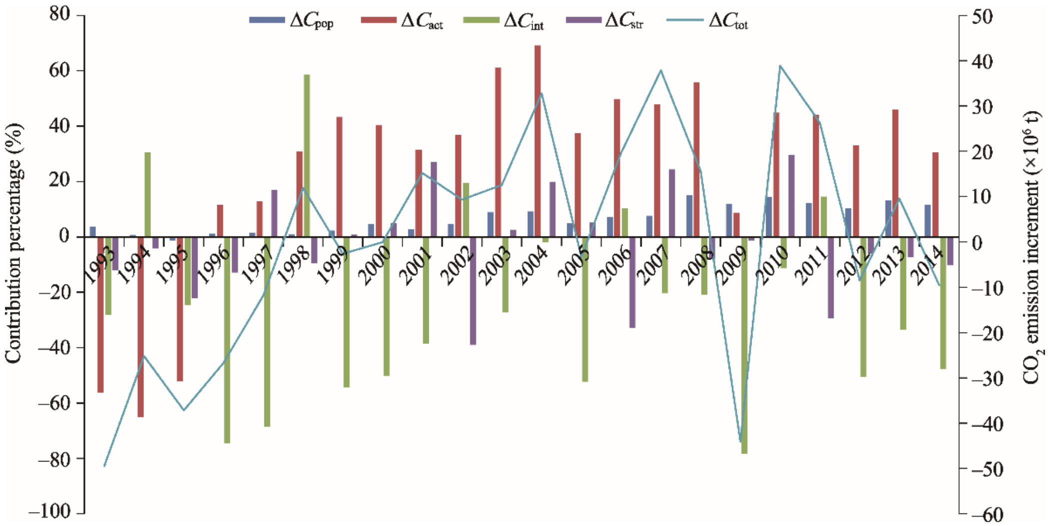

Fig. 4 Additive LMDI (logarithmic-mean Divisia index) decomposition of CO_2 emissions from 1992 to 2014 in Central Asia. The line graph indicates the yearly incremental change of the total CO_2 emissions. The bar graph indicates the contribution percentage of each influence factor on CO_2 emission. The positive values represent the driving effects of influences factors, while the negative values indicate the inhibiting effects of influences factors. ΔC_{pop}, the population effect; ΔC_{act}, the economic active effect; ΔC_{int}, the energy intensity effect; ΔC_{str}, the energy carbon structure effect; ΔC_{tot}, the total CO_2 emission increment.

3.3.2 LMDI decomposition of CO_2 emissions in each of the five Central Asian countries

The contributions of influence factors to the total CO_2 emissions in the five Central Asian countries were explored and compared with each other, as shown in Figures 5 and 6.

This analysis demonstrated that the population effect and economic active effect are the two driving factors on CO_2 emissions during 1992–2014 in all countries. The economic active effects in Kazakhstan, Turkmenistan and Uzbekistan were particularly significant, leading to the increments of CO_2 emissions of 119.17×10^6 (contribution percentage of 41.46%), 50.07×10^6 (contribution percentage of 52.69%) and 85.55×10^6 t (contribution percentage of 32.91%), respectively. Although Turkmenistan had lower CO_2 emissions, the economic active effect contributed to most of the CO_2 emissions in this country. Due to a considerable population growth during the study period, the population effect was particularly high in Uzbekistan, leading to an increase in CO_2 emissions by 41.13×10^6 t.

The energy intensity effect was the main inhibiting factor on CO_2 emissions in the five Central Asian countries. Specifically, the largest decrease in CO_2 emissions occurred in Kazakhstan and Uzbekistan, with CO_2 emission reductions of -139.74×10^6 and -121.48×10^6 t, respectively. The larger inhibiting contribution percentages of this factor were however recorded in Kyrgyzstan and Tajikistan, with the contribution values of –60.61% and –54.7%, respectively (the total CO_2 emission reductions of -1.61×10^6 and -2.13×10^6 t, respectively). The energy intensity effect also had a relatively large inhibiting contribution to the total CO_2 emissions in Kazakhstan (contribution percentage of –48.62%). The energy carbon structure effect generally played a relatively minor role on the total CO_2 emissions in Central Asia. It tended to inhibit CO_2 emissions in all countries except for Kyrgyzstan.

Overall, the total CO_2 emissions during the study period decreased in Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan (decreased by -13.73×10^6, -1.61×10^6, -2.13×10^6 and -6.59×10^6 t, respectively), while increased in Turkmenistan (increased by 35.39×10^6 t). The special case of

Turkmenistan might be due to the higher energy consumption. Nevertheless, the driving effects of CO_2 emissions could have been favored by the lack of energy efficiency and conservation policies in this country (Dong et al., 2016).

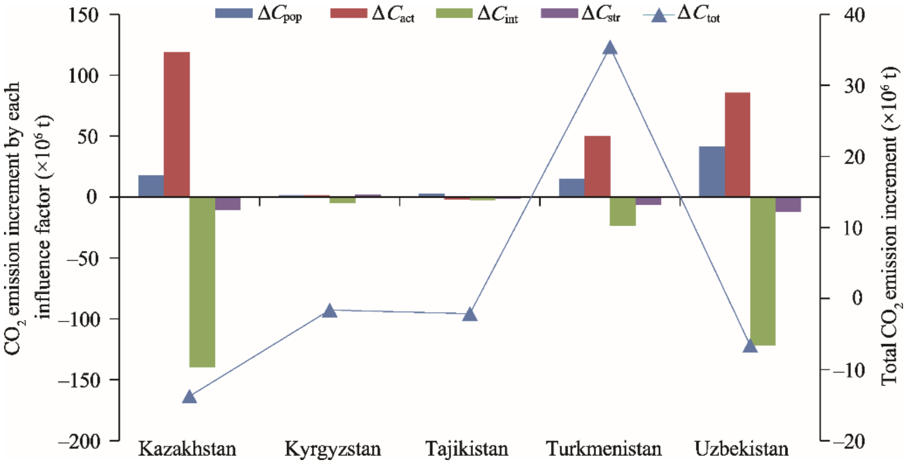

Fig. 5 CO_2 emission increment by each influence factor and the total CO_2 emission increment in the five Central Asian countries during 1992–2014

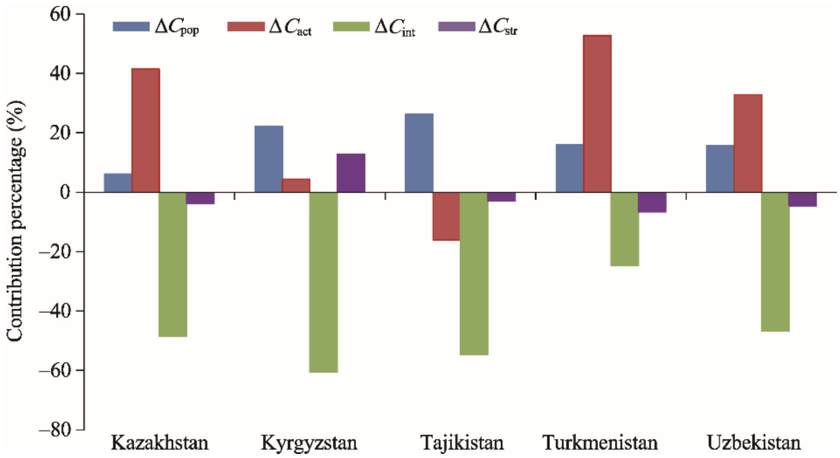

Fig. 6 Contribution percentage of each influence factor to the total CO_2 emissions in the five Central Asian countries during 1992–2014

3.4 Decoupling index based on the additive LMDI decomposition results

In this study, we explored the relationship between CO_2 emissions and economic growth in Central Asia using a decoupling index, based on the additive LMDI decomposition results. The advantage of this decoupling index is that it can express detailed decoupling information for each influence factor, including population, energy intensity and energy carbon structure.

The decoupling results (Table 2) included three statuses: strong decoupling, relative decoupling and no decoupling. The total decoupling index indicated the occurrence of strong decoupling during the periods of 1996–1997 and 1999–2000, and in the years 2005, 2009, 2012 and 2014. These indications are consistent with the decoupling elasticity results. Relative decoupling occurred in the year 1994, during the period of 2001–2003, and again in the years 2006, 2008, 2011 and 2013. For all other years, there was no decoupling. Overall, CO_2 emissions in Central Asia were strongly related to economic growth, except for a few years of strong decoupling that resulted from social and financial crises.

The influence factors of CO_2 emissions showed almost no decoupling in respect to population, perhaps due to population growth. Moreover, the energy carbon structure showed either no or only a relative decoupling, suggesting a lack of optimization in its use and only a slight degree of

degeneration over several years. Notably, energy intensity experienced a strong decoupling over nine years (1996, 1997, 1999, 2000, 2001, 2005, 2009, 2012 and 2014), i.e., it likely played a critical role in reducing CO_2 emissions and prompting decoupling from economic growth. Hence, we suggest that more advanced energy-use technologies are needed to improve energy efficiency.

Table 2 Decoupling results based on additive LMDI (logarithmic-mean Divisia index) decomposition between CO_2 emissions and economic growth in Central Asia

Time period	δ		δ'_{pop}		δ'_{int}		δ'_{str}	
	Value	Status	Value	Status	Value	Status	Value	Status
1992–1993	–0.6476	ND	0.0656	RD	–0.5005	ND	–0.2127	ND
1993–1994	0.4070	RD	0.0005	RD	0.4700	RD	–0.0636	ND
1994–1995	–0.9185	ND	–0.0242	ND	–0.4704	ND	–0.4239	ND
1995–1996	7.4677	SD	–0.0912	ND	6.4534	SD	1.1055	SD
1996–1997	3.8915	SD	–0.1152	ND	5.3316	SD	–1.3249	ND
1997–1998	–1.6248	ND	–0.0317	ND	–1.8981	ND	0.3050	RD
1998–1999	1.1971	SD	–0.0509	ND	1.2545	SD	–0.0066	ND
1999–2000	1.0036	SD	–0.1151	ND	1.2400	SD	–0.1213	ND
2000–2001	0.2779	RD	–0.0863	ND	1.2253	SD	–0.8611	ND
2001–2002	0.4041	RD	–0.1289	ND	–0.5269	ND	1.0599	SD
2002–2003	0.2592	RD	–0.1450	ND	0.4460	RD	–0.0419	ND
2003–2004	–0.3948	ND	–0.1333	ND	0.0260	RD	–0.2875	ND
2004–2005	1.1229	SD	–0.1344	ND	1.3936	SD	–0.1363	ND
2005–2006	0.3108	RD	–0.1433	ND	–0.2082	ND	0.6623	RD
2006–2007	–0.2443	ND	–0.1596	ND	0.4262	RD	–0.5109	ND
2007–2008	0.2489	RD	–0.2698	ND	0.3737	RD	0.1450	RD
2008–2009	7.9163	SD	–1.3733	ND	9.1344	SD	0.1552	RD
2009–2010	–0.7281	ND	–0.3207	ND	0.2511	RD	–0.6586	ND
2010–2011	0.0573	RD	–0.2763	ND	–0.3304	ND	0.6640	RD
2011–2012	1.4022	SD	–0.3113	ND	1.5306	SD	0.1828	RD
2012–2013	0.6022	RD	–0.2855	ND	0.7265	RD	0.1612	RD
2013–2014	1.5129	SD	–0.3817	ND	1.5587	SD	0.3358	RD

Note: δ, the total decoupling index; δ'_{pop}, δ'_{int} and δ'_{str}, the decoupling in population, energy intensity and energy carbon structure in the i^{th} year, respectively; SD, strong decoupling; RD, relative decoupling; ND, no decoupling.

4 Conclusions and policy implications

Energy-related CO_2 emissions in Central Asia decreased during 1992–1998 and increased during 1999–2014. CO_2 emissions were not completely decoupled from economic growth, i.e., the main status corresponded to a "weak decoupling".

The economic active effect and population effect were the main driving factors of CO_2 emissions, with contribution percentages of 39.08% and 11.80%, respectively. Moreover, the energy intensity effect and energy carbon structure effect represented the inhibiting factors of CO_2 emissions, with contribution percentages of –44.82% and –4.32%, respectively.

The contribution percentage of each influence factor was different in the five Central Asian countries. The increment of the total CO_2 emissions decreased in almost every country except for Turkmenistan (increased by 35.39×10^6 t during the study period). Kazakhstan, Turkmenistan and Uzbekistan were the three main energy consumption countries, with annual average CO_2 emissions of 189.69×10^6, 45.54×10^6 and 115.38×10^6 t, respectively. In fact, Kazakhstan has been mainly relying on solid fuel consumption to develop its economy, while Turkmenistan and Uzbekistan on gas fuel. Kyrgyzstan and Tajikistan have lower energy reserves; hence, both of them have developed their economies relying mainly on the primary sector.

In order to realize a low-carbon economy in Central Asia, we suggest four key policy suggestions based on the results of this study. First, the industrial structure should be adjusted and the economic

development mode should be changed. Specifically, the Central Asian countries need to reduce their reliance on the secondary industry and develop their tertiary industry (e.g., tourism and other services). Additionally, emerging industries should be encouraged and international cooperation should be strengthened to achieve information industrialization and economic transformation. Second, energy should be utilized more efficiently and the supervision of industrial enterprises should be improved. Specifically, the Central Asian countries should acquire new emission reduction techniques (e.g., pollution treatment, waste disposal, cleaner production technologies, etc.). At the same time, high-pollution enterprises should undertake responsibility through accountability and higher taxation. Third, renewable energy resources should be developed further and the energy utilization structure should be optimized. Central Asia owns abundant renewable energy resources (e.g., wind power, solar energy, hydropower energy and biomass energy) that have an outstanding exploitation potential. That is to say, Central Asian countries can effectively replace traditional high-polluting energies with renewable energies by optimizing their utilization structure. Fourth, laws, regulations and public awareness on environmental protection issues should be improved. Central Asian governments should advocate for a "green consumption" through the media or educational organizations, guiding and encouraging the population in the use of recycled and "green products" in everyday life. Through these actions, Central Asia would be able to reduce CO_2 emissions and build a resource-conserving and environment-friendly society.

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